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DISCOVERY OF PULSED X-RAYS FROM THE SMC TRANSIENT RX J0052.1-7319

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ABSTRACT

Coherent 65 mHz pulsations in the X-ray flux of the Small Magellantic Cloud (SMC) transient source RX J0052.1-7319 have been detected by us in an analysis of ROSAT data. We report on the pulsations we detected in ROSAT HRI data and simultaneous detection of these pulses in hard X-rays using BATSE data. The BATSE data show an outburst of the source lasting 60 days. We report on optical observations of the candidate companion, and a new source position we determined from the HRI data, which is consistent with the candidate's location. From the measured fluxes and observed frequency derivatives we exclude the possiblity that the pulsar is in the foreground of the SMC, and show that an accretion disk is present during the outburst, which peaked near Eddington luminosity.

Subject headings: accretion, accretion disks – binaries: general – pulsars: individual (RX J0052.1-7319) – X-rays : stars

1. INTRODUCTION

RX J0052.1-7319 is an X-ray source located in the the Small Magellanic Cloud, first detected with Einstein (1E 0050.3-7335, Wang & Wu 1992). It was classified by Kahabka and Pietsch (1996) as a transient X-ray binary candidate based on the ROSAT PSPC data from October 1991 and April 1992.

As part of a systematic search of the ROSAT data for pulsed sources, we have discovered pulsations from RX J0052.1-7319 at a frequency of 65.4 mHz (period = 15.3 s) using ROSAT HRI observations from 1996 November-December. Our search had previously detected another SMC pulsar, J0117.6-7330 (Macomb et al. 1999).

After a preliminary report of our discovery of the pulsar nature of RX J0052.1-7319 (Lamb et al. 1999), Kahabka estimated a new source position based on HRI observations of 1995 May (Kahabka 1999a), and confirmed the detection of pulsations using an HRI observations from October 1996 (Kahabka & Pietsch 1996). Israel et al. (1999) identified a Be star as the likely optical counterpart to the source. Udalski (1999) then reported on the long term optical variability of this candidate, based on Optical Gravtational Lensing Experiment (OGLE) monitoring.

Here we report on the pulsations we detected in the ROSAT HRI data, detection of these pulses in hard X-rays using simultaneous BATSE data, the history of the outburst visible in the BATSE data, and optical observations of the candidate companion and nearby stars.

2. OBSERVATIONS

We initially discovered pulsations from RX J0052.1-7319 in observations made with the High Resolution Imager (HRI) detector of the ROSAT (Trümper 1983) in 1996 November and December. The HRI, which consisted of two cascaded microchannel plates (MCPs) with a crossed grid position readout system, was sensitive to X-rays in the $\sim 0.2 - 2$ keV range. Thereafter we detected the pulsations in observations from the Burst and Transient Source Experiment (BATSE) (Fishman 1989) on the CGRO using data from the Large Area Detectors (LADs) which are NaI scintillation detectors sensitive to hard X-rays/soft gamma-rays in the 20 keV to 2 MeV range.

2.1. *ROSAT Observations*

Our discovery was made in the ROSAT HRI observations of 1996 November 10.71 – December 9.16 as part of a systematic search of the ROSAT data for previously undetected pulsars. These data were among 1365 data sets we selected from the catalog of 59911 ROSAT/HRI point source observations based on the potential for detection of significant pulsations. Each data set was processed using standard Ftools, with barycentered arrival times for the first 200 ks of each observation binned with 5 ms resolution, and Fourier transformed. The power spectra were searched for significant pulsed signals unassociated with the ∼5760 s spacecraft orbit or the 402 s period spacecraft orientation wobble. The RX J0052.1-7319 HRI observations were selected for further analysis because of a strong signal near 65 mHz.

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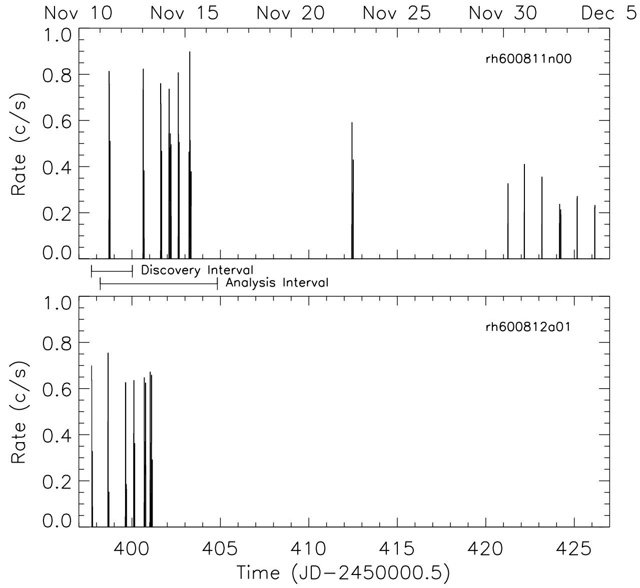

FIG. 1.— Mean count rates in 1000 s bins for the 1996 November 11 (MJD 50398) – December 9 ROSAT HRI observations of RX J0052.1-7319 showing the time structure of the observation window, and the declining flux of the source. The upper panel is for observation rh600811n00 and the lower for rh600812a01. Between the panels is shown both the time interval for the initial FFT in which the pulsations were discovered, and the interval used for the analysis resulting figures 2 and 3.

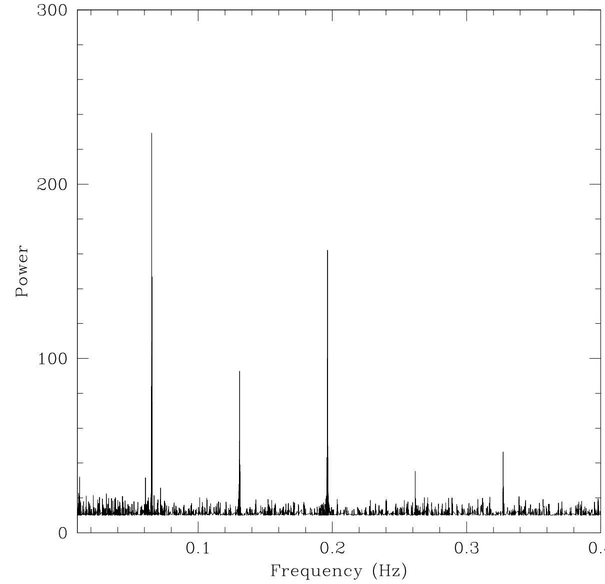

FIG. 2.— Rayleigh periodogram for the 1996 Nov 11.21-16.83 ROSAT HRI observations of RXJ 0052.1-7319. This was implemented with an FFT of data binned with 0.5 s resolution. A fractional frequency derivative of $\dot{\nu}/\nu = 8.37 \times 10^{-10}$ s^{-1} is accounted for in the analysis. Only values above 10 are plotted. The pulse frequency, near 65 mHz, and four harmonic overtones are clearly detected. The structure in the wings of each peak is due to the non-uniform spacing of the data.

These HRI observations, rh600811n00 and rh600812a01, are of two SMC fields which contain RX J0052.1-7319. The observations for these two fields are partially contemporaneous. Figure 1 shows the count rates in 1000 s bins for events within $60''$ of the source in these observations. The roughly 10-20% difference in counting rates between contemporaneous portions of the two observations may be due principally to differences in source vignetting. For observation rh600812a01, the source is $17'$ from the center of the HRI field and vignetting corrections are 10-20%; for observation rh600811n00 the source is $8\overset{\prime}{.}4$ from the HRI center and vignetting is substantially less. From observation rh600811n00 it is clear that the source flux is declining.

As can be seen in Figure 1, the initial 200 ks (2.3 days) interval of the observations, which was used for the initial search fft, contained only a portion of either of the two observations. We chose for further analysis the data of Nov 11.21-16.83 (all of rh600812a01 and the first portion of rh600811n00).

From initial analyses of this dataset we knew pulse frequency was changing significantly, and that there was substantial power at higher harmonics of the pulse frequency. To accurately estimate the pulse frequency and frequency derivitive we maximized the Z_3^2 statistic (Buccheri et al. 1983), where $Z_3^2(f) = p(f) + p(2f) + p(3f)$, and the Rayleigh statistic $p(f)$ is calculated as:

$$p(f) = \frac{2}{N} \left| \sum_{k=1}^{N} exp(i2\pi f[t_k + {}^{1}\!/_{2}\alpha(t_k - \tau)^2]) \right|^2 . \quad (1)$$

Here N is the number of photons detected in the interval, f is the analysis frequency, $\alpha = \dot{\nu}/\nu$, with ν the pulse frequency, t_k is a barycentric arrival time of photon k, and τ is an epoch within the data interval.

For epoch MJD 50401.0 (1996 Nov. 14.0) we obtained ν = 0.06545850(7) Hz and $\dot{\nu} = 5.48(7) \times 10^{-11}$ Hz s^{-1}. The maximum value of Z_3^2 was 524, which is highly improbable by chance.[1] The Rayleigh statistic for this ratio of $\dot{\nu}/\nu$ is shown in figure 2. In addition to the pulse fundamental, four pulse harmonic overtones are clearly detected.

The HRI data from the 1996 November 11.21-16.83 interval epoch-folded with this ephemeris is shown in figure 3. The pulse profile has a single asymmetric peak, with a narrow valley at minimum. The pulsed fraction ([mean-minimum]/mean) is 35 ± 3%.

For the HRI data from the interval 1996 December 5-9 we obtain a frequency $\nu = 0.0655330(3)$ Hz at epoch MJD 50524.0, and $\dot{\nu} = 2.3(2) \times 10^{-11}$ Hz s^{-1}. Thus the decrease in counting rate noted above was accompanied by a decrease in spin-up rate, as would be expected from the intrinic correlation between mass accretion rate and angular momentum accretion rate in a disk fed accreting pulsar.

For the 1996 November 11-16 and December 5-9 intervals we find source count rates of 0.92 and 0.46 counts s^{-1} respectively. These rates are corrected for vignetting (David et al. 1999) and the $15''$ radius circle used to select the data, using the HRI off-axis encircled energy profile (Boese 2000).

[1] We estimate that the probability of obtaining a Z_3^2 of 524 or more due to Poisson noise is less than 10^{-98}, including the number of trials introduced by searching in frequency and frequency derivative. This calculation however neglects systematic signatures in the data, which would likely play a dominate role any false detection with a Z_3^2 this large.

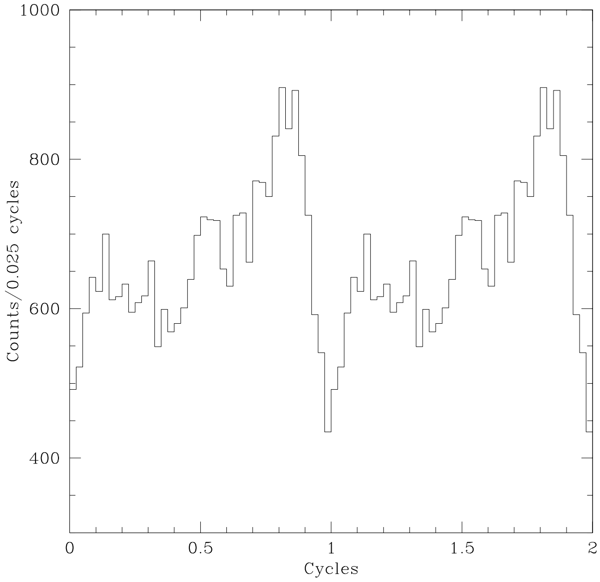

FIG. 3.— Pulse profile of RXJ 0052.1-7319 from the ROSAT HRI observations of 1996 Nov 11.21-16.83.

To estimate fluxes from these count rates we have used the spectrum estimated for the source by Kahabka & Prietsch (1996) based on a fit of ROSAT PSPC data. This consists of thermal bremsstrahlung model with $kT = 17$ keV, a galactic absorption column of $3 \times 10^{20}\mathrm{cm}^{-2}$, and an absorption column within the SMC with density of $N_H = 7.0 \pm 4.0 \times 10^{21}\mathrm{cm}^{-2}$ (95% confidence errors), with metallicities reduced by a factor of seven from solar system abundances. This model results in 0.1-2.0 keV unabsorbed flux estimates of $5.9 \pm 1.0 \times 10^{-11}\mathrm{erg\ cm^{-2}s^{-1}}$ and of $3.0 \pm 0.5 \times 10^{-11}\mathrm{erg\ cm^{-2}s^{-1}}$ for the 1996 November 11-16 and December 5-9 intervals respectively.

Using the 1996 November data of observation rh600811n00, we have determined the position of the source to be R. A. $= 0^{\mathrm{h}}52^{\mathrm{m}}13\overset{\mathrm{s}}{.}65$, Dec. $= -73°19'19\overset{''}{.}5$, with a statistical uncertainty ($1''$) which is negligible in comparison to systematic position errors, which result in an 68% confidence error circle of radius $7''$ (Kürster 1993, ROSAT Users Handbook[2]). These systematic errors are due to uncertainty in the aspect of ROSAT. We note that this position differs by nearly 10" from the position quoted by Kahabka (1999b) and Kahabka (2000). However, since these latter determinations used either very low rate data (<0.01 c/s) or data in which the source was at the edge of the HRI field of view, we believe that the position given above may be the more accurate.

2.2. *BATSE Observations*

The Burst and Transient Source Experiment (BATSE) was an all sky monitor which flew onboard the Compton Gamma-Ray Observatory (CGRO). The data used in the analysis presented here were from the Large Area Detectors (LADs) which were NaI(Tl) scintillation counters 1.27 cm thick, with 2025 cm^2 area, that were located at the eight corner of the CGRO spacecraft. Count rate data from the LADs was continuously available from 1991 April to 2000 May, except during SAA passages and occasional telemetry outages.

The 20-50 keV channel of the BATSE LAD discriminator rates (DISCLA channel 1) were analysed for pulsations from RX J0052.1-7319 using techniques discussed in Finger et al. (1999). Rates were combined from different detectors with coefficients optimal for a source with a spectrum of the form $dN/dE = A * exp(-E/kT)/E$ with $kT = 20$ keV. A large number of pulse profiles are obtained by fitting short segments of these combined rates with a model consisting of a quadratic spline background, plus a low order Fourier expansion pulse profile model. These profiles are then combined over multiple day intervals using trial frequencies and frequency rates. The resulting combined profiles are evaluated with the Y_n statistic (Finger et al. 1999), which is simular to the Z_n^2 statistic, but accounts for possible non-Poisson noise.

Using data from the interval 1996 Nov 11.0–17.0, Y_3 was searched over a frequency range of width 10^{-4} Hz centered on the ROSAT measurement, and a frequency rate range of -10^{-11} Hz s^{-1} to 10^{-10} Hz s^{-1} resulting in maximum value of $Y_3 = 57.0$ which we estimate[3] has a probability of being exceeded by chance of less than 2×10^{-7}. The resulting frequency and frequency rate estimates were $\nu = 0.06545830(10)$ Hz at epoch MJD 50401.0, and $\dot{\nu} = 5.62(12) \times 10^{-11}$ Hz s^{-1}, in good agreement with the ROSAT results.

The BATSE pulse profile for this interval using the ROSAT HRI ephemeris is shown in figure 4. The profile is shown relative to the mean flux level, which cannot be determined from the data due to the weakness of the source and the high background level. The solid curve is the profile corresponding to six Fourier coefficients which have been estimated with the same fitting technique used with the frequency search. Error bars for the value of the curve at 13 approximately independent points are shown. Six harmonics were chosen because this approximately matches the 1.024 s resolution of the data.

Pulsations were then detected in nine additions six-day intervals, extending the total period the source was detected with BATSE to 60 days between 1996 September 18 and November 17. Beginning with the Nov 11-17 interval, the total period of detection was progressively extended outward by frequency and frequency rate searches in the adjacent six day intervals, using $5 \times 10^{-5} Hz$ frequency ranges centered on the extrapolation from the neighboring frequency and frequency rate estimate, and the frequency rate range given above. Searching in this manner at the boundaries of the known frequency history reduces the required frequency search range, providing the best sensitivity. Figure 5 shows the resulting measurements of frequency, frequency rate, and r. m. s. pulsed flux in the 20-50 keV energy band. The figure also shows for comparison the frequency and frequency rate measurements from the ROSAT HRI data.

[2]http://heasearc.gsfc.nasa.gov/docs/rosat/ruh/handbook/node34.html

[3]This estimate approximates the distribution of Y_3 with the chi-squared distribution with 6 degrees of freedom, which is valid in this case because of the large number of profiles being combined, and accounts for 1100 independent trials.

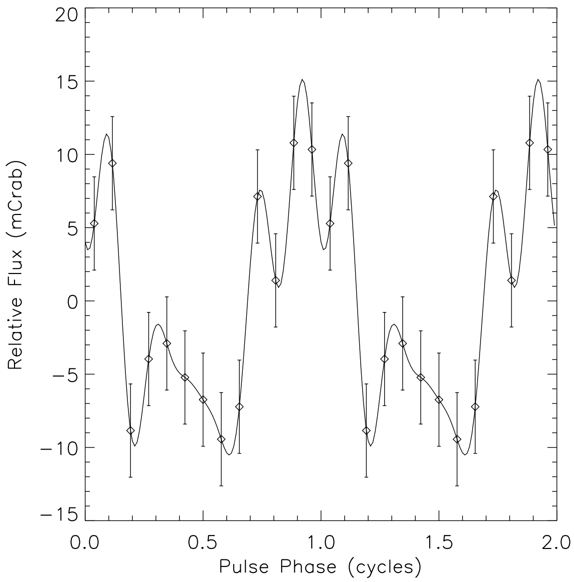

FIG. 4.— Pulse profile of RXJ 0052.1-7319 from the BATSE observations of 1996 Nov 11.0-17.0. This profile is based on an estimated six harmonic Fourier model. Error bars are given for approximately independent points. This profile is folded with the same ephemeris at that in figure 3.

Efforts were made to detect the source from 1996 August 1 to September 18, and from 1996 November 17 to 1997 January 8, but these failed. These attempts used searches with a frequency range of 3×10^{-4}Hz centered on the nearest detection, and a frequency rate range of -10^{-11} Hz s^{-1} to 10^{-10} Hz s^{-1}. Prior to 1996 September 18, pulsations from the 130.4 mHz pulsar 4U 1626-67 interfered with first harmonic (i.e. $2 \times f$) contribution to Y_3, in a narrow frequency band near 65.2 mHz. For this narrow band, this harmonic was left out of the search. We conclude that in these intervals prior to and following our 1996 September 18 to November 17 detections that the source had pulsed flux below our sensitivity level. We estimate an upper limit of 8 mCrab for the 20-50 keV r. m. s. pulsed flux for these intervals.

2.3. *Optical Observations*

In figure 6 we show a V band image taken from South African Astronomical Observatory (SAAO) 1.0m telescope on 20 Jan 1999. Marked on the figure is the X-ray error circle of Kahabka (2000) which has a 6" radius, and the error circle from this work, with a 7" radius. The object marked A is the source identified as the counterpart by Israel et al. (1999) based upon a red spectrum. The objects labeled A, B, C, and D are also identified in Figure 7.

If the optical counterpart of RX J0052.1-7319 is a Be star, then it should show excess H_α emission. In figure 7 we show H_α versus R band counts for 25 stars in the vicinity of Kahabka's X-ray error circle. The line is a linear best fit through all the data points shown. Stars that lie above the line are ones that show an H_α excess – i.e. objects A, B and C as identified on figure 6. Object D, the one inside the Kahabka (2000) error circle, shows no excess. Objects B and C, though exhibiting an H_α excess, are too far away from the X-ray position to be the counterpart. If, as we might expect, the optical companion is a Be star, the only reasonable counterpart is object A, the star identified by Isreal et al. (1999). Object A is well contained with the error circle for RX J0052.1-7319 presented here, and thus the identification of the X-ray source as a member of a Be system seems reasonable.

The absolute V magnitude of object A may be determined from the value quoted by Udalski (1999) of m_v=14.67. The distance modulus to the SMC determined by Westerlund (1997) is $(m - M)_o = 18.9$. In addition, the average extinction is E(B-V) = 0.07-0.09 (Schwering & Israel 1991), though there are regions in the SMC where it can rise as high as 0.25. Combining these parameters leads to an estimate of M_v= -4.47$\pm$0.02. This magnitude corresponds to a star in the range B1III - B0V, very similar to the value obtained for Be/X-ray binary counterparts (e.g. that of RX J0117.6-7330 quoted in Coe et al. (1998)).

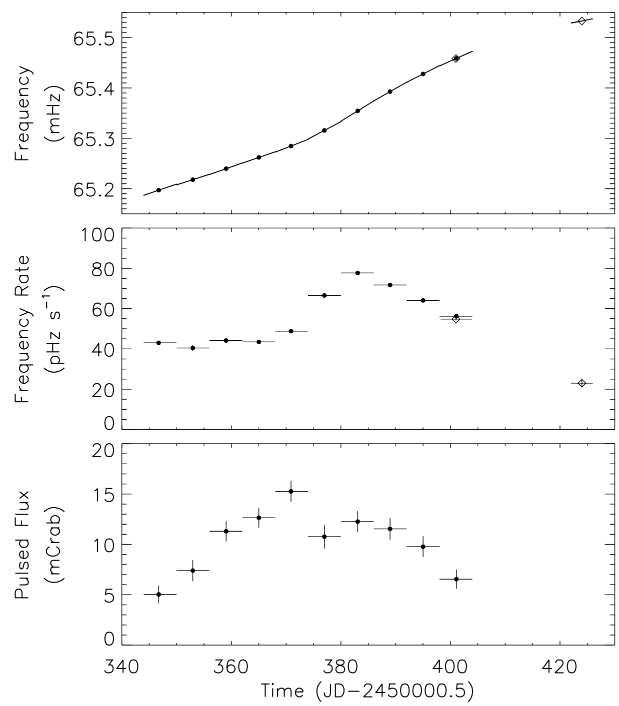

FIG. 5.— Pulse timing measurement for RX J0052.1-7319 from BATSE and ROSAT, and pulsed flux measurements from BATSE. The top panel shows the pulse frequency, with solid circles for BATSE measurements, and open diamonds for ROSAT HRI measurements. The lines through each point span the measurement interval, and have the slope of the measured frequency rate. The error bars are too small to be visible on the plot. The middle panel shows the pulse frequency rate, with solid circles for BATSE measurements, and open diamonds for ROSAT HRI measurements. The lines through each point span the measurement interval. The bottom panel shows the BATSE r. m. s. pulsed flux (20-50 keV). For reference 1 mCrab (20-50 keV) = 1.0×10^{-11} erg cm^2 s^{-1}, which corresponds to a luminosity of 4.3×10^{36}erg s^{-1} in the SMC. The plot covers the date range 1996 September 14 to December 23. For flux upper limits before and after the BATSE measurements presented see the text.

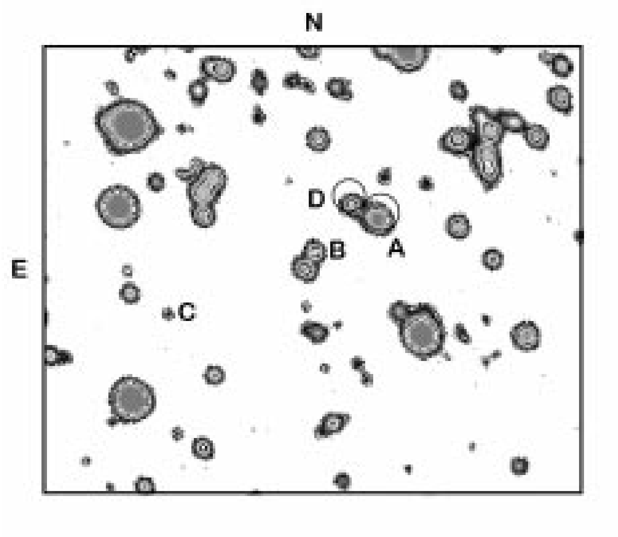

FIG. 6.— V band image taken from South African Astronomical Observatory (SAAO) 1.0m telescope on 20 January 1999. Marked on this figure is the X-ray error circle reported in Kahabka (2000) near Star D, and the error circle from this work located near Star A.

3. DISCUSSION

The ROSAT HRI observations we have presented show that RX J0052.1-7319 is a pulsar with a 65 mHz rotation frequency. Variations in the flux by more than two orders of magnitude between ROSAT observations at different epochs demonstrates that the source is a transient (Kahabka & Pietsch 1996,Lamb et al. 1999). The BATSE observations we have presented show that the November – December 1996 ROSAT HRI observations occurred on the tail of a outburst that began at least two months earlier, lasting more than 80 days.

The companions of transient pulsars with known spectral type are generally Be (or Oe) stars. There are now known a few transient pulsars in low-mass X-ray binaries, but these all have high spin frequencies ($\nu > 1$ Hz). Be stars show both emission in the Balmer lines, and an excess in the IR, due to a disk of material shed from the equator of the rapidly rotating star. The accretion of this material, which is thought to form a quasi-keplerian disk, fuels the X-ray outbursts.

Two types of outbursting behavior are observed in Be/pulsar binaries: type I ("normal" outbursts), with a series of lower luminosity ($L < 10^{37}$ erg s^{-1} outbursts occurring once per orbit, generally near periastron; and type II ("giant" outbursts), single high luminosity ($L \sim 10^{38}$ erg s^{-1} sometimes lasting several orbits (Stella, White & Rosner 1986). These outbursts are generally accompanied by rapid spin-up of the neutron star, indicating disk accretion (Finger, Wilson & Harmon 1996, Bildsten et al. 1997).

The BATSE observations presented here are consistent with a giant outburst of a Be/pulsar transient in the SMC. From the observed spin-up we can show that a disk is present, and the the source is outside our galaxy. In disk accretion, the angular momentum accreted per unit accreted mass is $l = (GMr_m)^{1/2}$, were M is the neutron star mass, and r_m the radius of the magnetosphere.

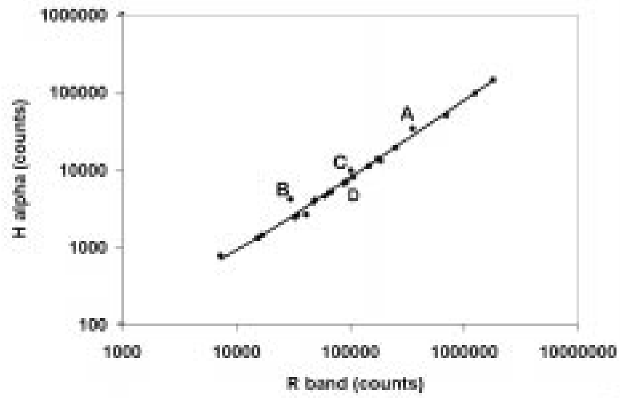

FIG. 7.— H_α versus R band plot of 25 stars in the vicinity of the X-ray error circle. Stars that lie above the line are ones that show an H alpha excess. Letters refer to stars identified in the previous figure.

The specific angular momentum for wind accretion is generally much less than this, since if it reaches this value, a disk forms. The magnetospheric radius is limited by the corotation radius $r_c = (GM)^{1/3}(2\pi\nu)^{-2/3} = 1.0 \times 10^9$ cm, where we have used $M = 1.4 M_\odot$. The specific angular momentum l is proportional to the ratio $\dot{\nu}/L$ where L is the pulsar's luminosity. Since the rate at which angular momentum is accreted is $l\dot{m} = 2\pi I\dot{\nu}$ where I is neutron star moment of inertia, and $L = GM\dot{m}/R$, where R is the neutron star radius, we have the upper limit

$$\frac{\dot{\nu}}{L} < (2\pi)^{-\frac{4}{3}}(GM)^{-\frac{1}{3}} I^{-1} R \nu^{-\frac{1}{3}} = 3.8 \times 10^{-49} \text{ Hz erg}^{-1} \quad (2)$$

where we have used a moment of inertia $I = 10^{45}$gm cm^2, and a radius $R = 10^6$ cm. For the Nov 11-17 observation, for which $\dot{\nu} = 5.6 \times 10^{11}$ Hz s^{-1}, this implies $L > 1.5 \times 10^{38}$ erg s^{-1}, and for peak frequency rate observed we have $L > 2.0 \times 10^{38}$ erg s^{-1}. Using the 0.1-2.0 keV flux $F = 5.9 \times 10^{-11}$ erg cm^{-2} s^{-1} observed in the 1996 Nov 11-17 HRI observation, we find the lower limit on the source distance of

$$d > 46 \left(\frac{\epsilon}{0.1}\right)^{\frac{1}{2}} \text{ kpc} \quad (3)$$

where ϵ is the fraction of the luminosity in the 0.1-2.0 keV energy band. This eliminates the possibility that the RX J0052.1-7319 is in the foreground of the SMC.

The limit in equation 2 is reached only with disk accretion. Using the measured frequency rate, fluxes, and the distance of 60 kpc to the SMC we find a ratio of $\dot{\nu}/L$ comparable to this limit, suggesting that an accretion disk is present during the outburst.

The pulse periods of Be binary pulsars range from 69 ms to 1400 s, with determined orbital periods ranging from 17 to 250 days. Corbet (1986) showed that the orbital period is correlated with the pulse period. From the observed distribution of spin and orbital periods we would expect an orbital period in the range of 25 – 100 days. In giant outbursts of Be/X-ray pulsars we expect a strong correlation of flux and frequency rate (see e.g. Finger, Wilson & Harmon 1996). We note however that the history of the frequency rate in fig 5 is dissimilar in profile to that of the pulsed flux. This could be due to the doppler signature of a binary orbit. An alternate explanation would be changes in the spectra or pulse fraction. However, giant outbursts typically have simple flux and intrinsic spin-up rate profiles, with a steady rise to peak, and a somewhat slower fall (see e.g. Parmar et al. 1989, Whitlock 1989, Finger, Wilson & Harmon 1996, but also, Negueruela et al. 1997).

The plausible identification of RX J0052.1-7310 as Be binary system in the SMC accentuates further the rather dramatic difference between the SMC and our Galaxy with regard to the population of high mass X-ray binaries. This fact has already been noted by several authors (Schmidtke et ak, 1999, Jokogawa et al. 2000). A recent compilation of the known X-ray pulsars[4] gives within the SMC one supergiant system, three known Be systems, and 11 transients with uncertain companion class (likely to be Be systems), making 15 high mass X-ray pulsar binaries. For the Galaxy the corresponding number is 40. Therefore, using a mass ratio of the SMC to the Galaxy of 1/100, this suggests that high mass X-ray pulsar systems in the SMC are overabundant by roughly a factor of 30 relative to the Galaxy. This analysis ignores the important effects of obscuration within the Galaxy, the relative frequency of observations, and the low luminosity sensitivites obtained for the Magellantic clouds; nevertheless the apparent disparity is remarkable.

Since high mass X-ray binaries have lifetimes which are a very small fraction ($\sim 10^{-3}$) of the age of the Galaxy, the dramatic difference between the SMC and the Galaxy points to a rather recent outburst of star-formation in the SMC within the last $\sim 10^7$ years. Further support of such an epoch of star formation comes from the radio observations of H1 by Stavely-Smith et al. (1997) and Putman et al. (1998), which show a strong bridge of material between the Magellanic Clouds and between them and our own galaxy. Furthermore, Stavely-Smith et al. have demonstrated the existence of a large number of supershells (created by multiple supernovae) of a similar age ($\sim$5 Myr), strongly suggesting enhanced starbirth has taken place as a result of tidal interactions between these component systems. Consequently it seems very likely that the previous closest approach of the SMC to the LMC $\sim 10^8$ years ago may have triggered the birth of many new massive stars which have given rise to the current population of HMXBs. In fact, other authors (e.g. Popov et al. 1998) claim that the presence of large numbers of HMXBs may be the best indication of starburst activity in a system.

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